The impact of Argo salinity profiles on the NCEP Global Ocean Data Assimilation System

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1 Introduction

For over 10 years the National Centers for Environmental Prediction (NCEP) has employed coupled ocean-atmosphere numerical models for making seasonal to interannual climate forecasts in an operational or quasi-operational mode (Ji et al., 1995; Ji et al., 1998; Saha et al., 2005). A critical element of the forecast effort is an ocean data assimilation system (ODAS) that provides an estimate of the ocean state to initialize the coupled forecasts. The original ODAS was based on the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 1 (MOM.v1) and was configured for the Pacific Ocean (Ji et al., 1995). The data assimilation method was a three-dimensional variational (3DVAR) scheme devised by Derber and Rosati (1989). The Pacific ODAS was later modified to incorporate revised background error covariances (Behringer et al. 1998) and to assimilate satellite altimetry data (Vossepoel and Behringer, 2000; Ji et al., 2000).

Over the last few years a new global ocean data assimilation system (GODAS) was developed to be the replacement for the Pacific ODAS, and to provide the oceanic initial conditions for the new NCEP coupled Climate Forecast System (CFS). The GODAS became operational in 2003 and the CFS went operational in 2004. A simple description of the GODAS is provided by Behringer and Xue (2004), and a more detailed paper is in preparation. As part of the development of the next version of the GODAS experiments have been run in which new data sets that are not used by the standard GODAS are introduced into the assimilation system. A report has been prepared on the first of these experiments in which TOPEX / Jason-1 and ERS-2 / Envisat altimetry have been assimilated (Behringer, 2005). The purpose of the present report is to describe the impact of using observed Argo salinity profiles in place of the synthetic salinity profiles used in the standard or operational GODAS. The report begins with a short description of the standard GODAS, continues with a description of how the observed salinity profiles are assimilated in conjunction with the synthetic profiles and concludes with a results section comparing the Argo salinity assimilation experiment with a Control that assimilates no data, with the standard GODAS and with the GODAS experiment that assimilates TOPEX / Jason-1 altimetry data.

2 The Standard Operational GODAS

The GODAS is based on a quasi-global configuration of the GFDL MOMv3 (Pacanowski and Griffies, 1998). The model domain extends from 75^{O}S to 65^{O}N and has a resolution of 1^{O} by 1^{O} enhanced to 1/3^{O} in the N-S direction within 10^{O} of the equator. The model has 40 levels with a 10 meter resolution in the upper 200 meters. This configuration represents a small improvement over the Pacific ODAS which had a 1.5^{O} resolution in the E-W direction and 28 levels in the vertical. Other new features include an explicit free surface, the Gent-McWilliams isoneutral mixing scheme and the KPP vertical mixing scheme. The GODAS is forced by the momentum flux, heat flux and fresh water flux from the NCEP atmospheric Reanalysis 2 (R2) (Kanamitsu et al. 2002). In addition the temperature the top model level is relaxed to weekly analyses of sea surface temperature (Reynolds et al., 2002), while the surface salinity is relaxed to annual salinity climatology (Conkright et al., 1999). Very short relaxation periods are used (5 days for temperature and 10 days for salinity). The GODAS assimilates temperature profiles and, in another new feature, assimilates synthetic salinity profiles as well. The assimilation method is the same 3DVAR scheme used in the Pacific ODAS, but it has been modified to assimilate salinity and the code has been rewritten to run in a multi-processor computing environment.

The standard GODAS has been used for a long reanalysis extending from 1979 to the present. In this reanalysis GODAS assimilates temperature profiles from XBTs, from TAO, TRITON and PIRATA moorings (McPhaden et al., 2001) and from Argo profiling floats (The Argo Science Team, 2001). The XBT observations collected prior to 1990 were acquired from the NODC World Ocean Database 1998 (Conkright et al., 1999), while the XBTs collected subsequent to 1990 are acquired from the Global Temperature-Salinity Profile Project. A synthetic salinity profile is computed for each temperature profile using a local T-S climatology based on the annual mean fields of temperature and salinity from the NODC World Ocean Database (Conkright et al., 1999). Figure 1 shows the monthly counts of the temperature profiles used in GODAS. The number of profiles can vary significantly from month to month, but there are longer term trends as well. For example, there is a gradual decline in the monthly counts after 1985 followed by a sharp recovery in 1990 when the source of the profiles changed.

There are also changes in the distribution of the profiles. For example, the TAO moorings represent a fixed array of daily observations in the tropical Pacific Ocean that has no counterpart in the 1980s. More recently the rapid growth of the Argo network represents both an important increase in the number of profiles and a departure from the older XBT network for which the profiles are confined to ship tracks. Figure 2 gives some flavor of the changes in the geographical distribution of the profiles, most notably the expansion of the Argo array between 2002 and 2004 and the improvement in coverage of the southern hemisphere during this time. All of these changes in the data suite will have an impact on the GODAS analysis. However, for this report we are only concerned with the period of 2000 through 2004 during which number of Argo salinity profiles increased significantly. While within this period the Argo network grows rapidly, the Tao array remains relatively constant and the abrupt discontinuity in 1990 in the XBT distribution is avoided.

3 The assimilation of Argo salinity profiles

The standard GODAS 3DVAR scheme is essentially the same as the original Derber and Rosati (1989) scheme, although it has been adapted to assimilate salinity in addition to temperature. Therefore the only change that was made for the Argo salinity experiment was to replace, whenever possible, the standard GODAS synthetic salinity profile associated with an Argo temperature with an observed Argo salinity profile. If an Argo temperature profile lacked an associated observed salinity profile, the synthetic profile was retained. The synthetic profiles associated with XBT and mooring temperature profiles were also retained. Figure 3 shows the monthly counts of Argo profiles for the period of the salinity experiment (2000 – 2004). During this period the number of Argo temperature profiles increased from 700 profiles / month to 4600 profiles / month, while the number of salinity profiles increased from 160 profiles / month to 4400 profiles / month. At the same time the total number of XBT and mooring profiles grew from about 4400 profiles / month to about 5900 profiles / month. Thus, over the course of the experiment, while the absolute number of observed salinity profiles grew by a factor of 30, the percentage of observed salinity profiles grew more slowly from 3% of the total to about 40%.

A comparison of the synthetic salinity profiles used in the standard GODAS with their observed counterparts is shown in Figure 4 for 5 latitude bands. Below about 200 m in the equatorial band and in the northern hemisphere the mean synthetic salinity and the mean observed salinity are essentially equal, while in the southern hemisphere the mean synthetic salinity is saltier than the mean observed salinity by 0.03 psu. Again below 200 m, the RMS difference between the synthetic and observed salinities tends to be larger in the northern hemisphere (0.1 psu) and generally smaller in the equatorial band (0.03 psu) and in the southern hemisphere (0.05 psu below 400 m). Above 200 m, in the 3 middle latitude bands, the mean synthetic salinities are too fresh by as much as 0.05-0.15 psu at 50-100 m below the surface. As might be expected the RMS differences are largest at the surface ranging from 0.2 psu in the southern hemisphere to 0.4 psu in the northern hemisphere.

Before combining the synthetic and observed salinity profiles in a single experiment, we made two adjustments to the synthetic profiles based on the data summarized in Figure 4. First, we applied a mean correction to each synthetic profile and, second, we increased the expected error assigned to each synthetic profile. To do this we first binned the synthetic minus observed profile differences into 5^o latitude by 10^o longitude boxes and computed the mean and RMS differences. These results were then mapped onto the model grid. Figure 5 shows slices from these fields at the surface and in an equatorial section. These data were further interpolated to the positions of the synthetic profiles where the mean difference was subtracted from the synthetic profile and the square of the RMS difference was added to the square of a background observation error. A background observation error is assigned to all salinity profiles, synthetic and observed alike, and is intended to account for the mismatch between what is measured by a single profile and what can be resolved by the numerical model. In this experiment, as in the standard GODAS, the background error for salinity is assigned the global value of 0.1 psu.

4 Evaluation

In this section the results of the Argo salinity assimilation experiment are compared to satellite altimetry data, island tide gauge data, Argo temperature and salinity profiles and zonal current profiles from the TAO array. To evaluate the impact of the salinity data on the GODAS, the same comparisons will be made using the results from the standard GODAS reanalysis, from the GODAS experiment that assimilates TOPEX / Jason-1 altimetry and from a Control run of the ocean model that is forced by the same R2 data but that does not assimilate any observations. Table 2 summarizes the model experiments.

4.1 Comparisons with satellite altimetry

For the purpose of these comparisons a simple OI scheme was used to map the TOPEX/Jason satellite altimetry to the GODAS grid. The maps represent monthly deviations of SSH from the 1993-99 mean. The altimetry data are independent of both GODAS runs considered here as well as the Control run. In the comparisons that follow each field has also had its own mean monthly climatology removed so that only the anomaly fields are compared. The altimetry anomalies were compared to the monthly average SSH anomalies from the Control, the standard GODAS analysis, and the GODAS analysis that assimilates the Argo salinity data. Figure 6 shows the correlations and RMS differences between the observations and the model results for the period 2000-2003. Considering all the comparisons together, while the performance of the Control is slightly worse in the western tropical Pacific Ocean and the equatorial Atlantic Ocean, there is not a great deal of difference among the 3 model runs for this time period. This was not the case in an earlier comparison of the Control and standard GODAS with TOPEX/Jason altimetry over the 1993-2003 period (Behringer, 2005). In that earlier comparison the performance of the standard GODAS was similar to that seen here in Figure 6, but the performance of the Control was considerably poorer outside the equatorial Pacific Ocean and throughout the entire Atlantic Ocean. For the much shorter period considered here, the main effect of the data assimilation in the standard GODAS appears to be an improvement in the SSH in the western tropical Pacific. Finally, in the bottom panels of Figure 6 the GODAS analysis that assimilates the Argo salinity data appears to perform very much like the standard GODAS in this comparison, but with a slight improvement in the vicinity of the ITCZ in the eastern Pacific Ocean.

4.2 Comparisons with island tide gauges

In this and subsequent comparisons, along with the Control, standard GODAS and Argo salinity runs, we will include a GODAS run that assimilates TOPEX / Jason-1 altimetry data along with temperature and synthetic salinity profiles. We begin here by comparing all the model outputs with island tide gauge data. The tide gauge data are not assimilated and are thus independent of the model runs. Research quality tide gauge data were acquired from the University of Hawaii Sea Level Center in the form of monthly average SSHs. Information about the gauges used here is listed in Table 3. The comparisons are confined to the tropics, six in the Pacific Ocean and one in the Atlantic Ocean. The time-series are shown in Figure 7 for the tide gauge SSHs and the model SSHs interpolated to the gauge locations. Each time-series has its own mean removed. The RMS differences and correlations for each tide gauge / model pair are listed in Table 4. The gauges shown in Figure 7a are near or outside the margins of the TAO array in the western Pacific. The Control captures the large events, but it also has large departures from the tide gauge records, most noticeably at Guam and Majuro. The assimilation of temperature and salinity data largely corrects the standard GODAS analysis and the GODAS analysis assimilating Argo salinity. The assimilation of TOPEX / Jason-1 altimetry data corrects the GODAS analyses still further. For these latter analyses the RMS errors are 2-3 cm and the correlations with the tide gauge SSH range from 0.76 at Pago Pago, where the standard deviation of the tide gauge record is low (3.21 cm), to 0.92 at Guam (Table 4). Figure 7b shows three gauges that are within one degree of the equator, two in the western Pacific and one in the Galapagos in the eastern Pacific. In the east, at Santa Cruz, the SSH's from the GODAS runs are well correlated with the tide gauge data at 0.93 or better and have RMS differences of about 2 cm. The Control also does well at Santa Cruz with a correlation of 0.77 and an RMS difference of 3 cm. The GODAS runs do less well at Kapingamarangi in the western Pacific where they correlate with the tide gauge data at 0.82-0.85 and have RMS differences of about 3 cm. At Nauru the GODAS runs do more poorly yet during this time period and are less correlated with the tide gauge than the Control run (Table 4). However, it should be noted that the GODAS SSH's track better with the TOPEX / Jason-1 altimetry (also plotted in Figure 7) than with the tide gauge data. At Limetree Bay in the Atlantic basin all of the time-series are fairly well grouped during the first 4 years and all of them capture the same large scale maxima and minima. This tight relationship lasts up until January 2004, when the time series abruptly diverge (Figure 7c).

4.3 Comparisons with observed temperature and salinity profiles

The next comparisons are between the model analyses and observed temperature profiles from the Argo floats and from the TAO and PIRATA moorings for the years 2000-2004. All of the GODAS analyses assimilate these observations so they are only independent of the Control. The difference between a model analysis and an observed profile is formed by interpolating the 5-day model output to the time and position of the observation and subtracting the observed from the model profile. Figure 8 shows the profiles of the mean and RMS differences for 5 latitude bands: 65°S-30°S, 30°S-10°S, 10°S-10°N, 10°N-30°N and 30°N-65°N. The upper panel in Figure 8a shows the comparisons for the Control; the largest mean errors are about 1°C and the largest RMS errors are 2-2.5°C. The comparisons for the standard GODAS analysis are shown in the lower panel of Figure 8a. By assimilating these temperature data the mean differences are reduced to less than 0.06^{o}C and the RMS differences are reduced to less than 1.5^{o}C. In the tropics and subtropics the RMS differences drop off to less than 0.5^{o}C below 100 meters. The two panels in Figure 8b show the same comparisons for the TOPEX/Jason-1 and Argo salinity GODAS analyses. The altimetry data was only assimilated between 30^{o}S and 40^{o}N so the comparisons for the southernmost and northernmost bands in the upper panel are essentially unchanged from those for the standard GODAS. In the tropics and subtropics the temperature differences between the model and the observations above 400 meters are nearly the same for the TOPEX/Jason-1 analysis as for the standard GODAS analysis. However, below 400 meters the mean temperature differences for the TOPEX/Jason-1 analysis increase with depth to 0.25-0.5^{o}C. Thus, as noted in a previous report (Behringer, 2005) the assimilation of altimetry in this particular experiment improves the representation of SSH variability in GODAS while degrading slightly the temperature field below 400 meters. The Argo salinity analysis, on the other hand, slightly improves the representation of temperature in GODAS, reducing the maximum RMS difference from the observed temperature in the thermocline by about 0.2 ^{o}C (Figure 8b, bottom panel). Since the set of temperature profiles that are assimilated by GODAS are common to the standard and the Argo salinity analyses, this improvement in the temperature field is an indirect result of assimilating observed salinity profiles in place of synthetic profiles.

Similar comparisons were done between the model analyses and observed salinity profiles from the Argo floats. These profiles, of course, are not independent of the GODAS analysis that assimilates them, but they are independent of the standard GODAS and TOPEX / Jason-1 GODAS experiments and of the Control run. Figure 9 shows the comparisons for the same latitude bands as for the temperature comparisons in Figure 8. The upper panel in Figure 9a shows the comparisons for the Control. At the surface the mean errors range between -0.1and 0.2 psu while the RMS errors range between 0.4 and 1.2 psu. The comparisons for the standard GODAS analysis are shown in the lower panel of Figure 9a. It is clear that the assimilation of synthetic salinity greatly reduces the mean error in the salinity field and reduces the RMS error by about 50%. Nevertheless, a fresh bias remains in the standard GODAS between 50 and 100 m in the 3 middle latitude bands. As discussed earlier this same fresh bias is present in the synthetic salinity profiles and it has simply been assimilated into the standard GODAS. As was the case for the Control run, the largest errors in the standard GODAS are in the 10^{o}N to 30^{o}N latitude band. The upper panel in Figure 9b shows the salinity comparisons for the TOPEX/Jason-1 GODAS analysis. As with the temperature comparisons the salinity comparisons for the southernmost and northernmost bands are essentially unchanged from those for the standard GODAS. Also, as with the temperature field there is a slight degradation in the salinity field when the altimetry is assimilated resulting in a slight increase in the RMS difference with the observed salinity in the tropics and subtropics. The bottom panel in Figure 9b shows the salinity comparisons for the GODAS analysis that assimilates Argo salinity profiles and corrected synthetic profiles. It is immediately clear that the fresh bias at 50-100 m has been effectively eliminated. At the surface the RMS difference has been reduced by 13% in the 10^{o}N to 30^{o}N latitude band and by 30%-35% elsewhere.

4.4 Comparison with current observations

A final set of comparisons was made between the model results and the zonal currents observed at five TAO locations along the equator in the Pacific Ocean. Table 5 lists their positions and the time periods for which data are available. Zonal currents from the model analyses were interpolated to the same times and locations as the observations. The means and standard deviations for all of these time series are shown in Figure 10. In the top panel the mean zonal currents in the three GODAS analyses are nearly identical; the assimilation of the altimetry data and the assimilation of Argo salinity profiles have had little effect beyond what has already been achieved by the assimilation of temperature and synthetic salinity in the standard GODAS. East of the dateline all of the model analyses get the depth of the undercurrent core reasonably correct. The magnitude of the undercurrent in the GODAS analyses is good at 170^{o}W and 140^{o}W, but it is too weak at 110^{o}W. The undercurrent in the Control is too weak at all three locations. In the GODAS analyses the eastward flow beneath the undercurrent core at 110^{o}W and below 200 m elsewhere is too strong and the westward surface flow at 170^{o}W and 140^{o}W is too weak. The Control run displays none of these deficiencies, suggesting that they may be artifacts of the assimilation process. West of the dateline, at 147^{o}E all of the model currents have an eastward bias over most of profile depth and they fail to capture the change in direction seen in the observations at 150 m. At 165^{o}E the undercurrent core in all of the model runs is too shallow and too broad. Also at 165^{o}E the currents in the GODAS analyses are too strong to the east between 50 and 150 m and too strong to the west above 50 m, while the currents in the Control run are reasonably good in these layers.

The lower panel in Figure 10 shows profiles of the standard deviation of the zonal flow at the five locations. The general agreement between the model and observed currents is good. The model current show less variability than observed in the layer just above the undercurrent core at 140^{o}W and 110^{o}W. The currents in the GODAS experiment that assimilates TOPEX/Jason-1 altimetry show more variability below 150 m at 165^{o}W and the currents in all the model experiments show this behavior at the westernmost site at 147^{o}E.

5 Discussion

The use of observed Argo salinity profiles has had a clear impact on the GODAS, both through their direct assimilation and through the statistics they provide for correcting the synthetic salinity profiles. In particular, the use Argo salinities has led to a broad general reduction in the RMS error in the GODAS salinity field and the elimination of a fresh bias below the mixed layer throughout much of the tropics and subtropics in the standard GODAS. Their use has also led indirectly to a small improvement in the GODAS temperature field. Nevertheless, there remain pre-existing problems in the standard GODAS that have not been improved by the assimilation of Argo salinities. For example, the undercurrent at 110^{o}W remains too diffuse and too weak, while the surface currents maintain an eastward bias at 170^{o}W and 140^{o}W and a westward bias at 14^{o}7E and 165^{o}E.

Some of these difficulties may be related to the fundamental problem of model bias that is common to all of these experiments. If we can succeed in reducing model bias through improvements to the model physics and to the forcing fields, we can expect the assimilation system to perform better regardless of the combinations of data that are assimilated.

Other simple technical improvements to the assimilation system may have a positive effect as well and these will be explored in the near future. The first of these is to extend the depth over which the assimilation is performed. In the experiments described here the data assimilation extends only down to 750 m, the typical depth limit of most XBT probes. Pushing the lower limit to 1500-2000 m would make better use of the growing number of Argo profiles and allow a greater range for temperature and salinity adjustments required by the assimilation of altimetry. A possible benefit to GODAS might be improved SSH without an increase in the RMS error in temperature and salinity below the thermocline. The second technical change would be to impose a partial geostrophic balance in the assimilation scheme. This has been shown to have a positive effect on the tropical and equatorial circulation (Burgers et al., 2002; Weaver et al., 2003) and may help to improve the surface equatorial currents in the western Pacific in GODAS.

Finally, it is reasonable to expect that the use of observed salinities will have a greater impact as the era of the Argo network lengthens. The experiment reported on here was only 5 years long and did not include an important El Nino or La Nina event. Also, as Figure 3 makes clear, over much of the 5 year period there were not many Argo salinity profiles available for assimilation.

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The tide gauge data were made available by the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu).

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Table 1. Satellite Mission Information

Satellite	Cycles	Start Date	End Date
TOPEX	002-364	1992-10-02	2002-08-11
Jason-1	022-074	2002-08-11	2004-01-18
ERS-2	001-085	1995-05-16	2003-06-22
Envisat	017-023	2003-06-22	2004-02-03

Table 2. Description of model experiments

Name	Forcing	Assim Data	Status
Control	Reanalysis 2	None	Developmental
GODAS - Standard	Reanalysis 2	Temperature, Syn. Salinity	Operational
GODAS – T / J	Reanalysis 2	Temp., Syn. Sal., Topex/Jason-1	Developmental
GODAS – Argo Salinity	Reanalysis 2	Temp., Syn. + Argo Salinity	Developmental

Table 3. Tide Gauge Information

Sta	Location	Country	Lat	Long	Years
053	Guam	USA Trust	13-26N	144-39E	1948-2004
005	Majuro-B	Rep. Marshall I.	07-07N	171-22E	1993-2003
056	Pago Pago	USA Trust	14-17S	170-41W	1948-2004
029	Kapingamarangi	Fd St Micronesia	01-06N	154-47E	1978-2001
004	Nauru-B	Rep. of Nauru	00-32S	166-55E	1993-2003
030	Santa Cruz	Ecuador	00-45S	090-19W	1978-2003
254	Limetree Bay	USA	17-42N	064-45W	1982-2004

Table 4. Tide Gauge vs Model Statistics (RMS of differences in cm)					
Location (TG std.dev. in cm)		**Control**	**Std GODAS**	**T/J GODAS**	**AS GODAS**
		2000-2004*		**2000-2003***	**2000-2004***
Guam (6.24)	RMS	7.22	3.62	2.59	3.07
	COR	0.57	0.87	0.92	0.88
Majuro (4.93)	RMS	5.42	4.31	3.05	3.77
	COR	0.40	0.72	0.82	0.72
Pago Pago (3.21)	RMS	2.90	3.03	1.93	2.93
	COR	0.60	0.65	0.76	0.66
Kapingamarangi (4.78)	RMS	3.60	3.19	2.65	2.90
	COR	0.67	0.82	0.85	0.83
Nauru (5.23)	RMS	4.32	4.86	4.16	4.76
	COR	0.58	0.40	0.64	0.42
Santa Cruz (4.75)	RMS	3.03	2.03	1.76	2.05
	COR	0.77	0.93	0.94	0.93
Limetree Bay (3.92)	RMS	3.46	3.14	2.49	3.83
	COR	0.53	0.68	0.81	0.60

* Nominal record lengths. Individual records may vary due to gaps in tide gauge records.

Table 5. TAO equatorial current observations	
Location	**Dates**
147E	1/2000-12/2000; 10/2002-10/2003
165E	1/2000-11/2004
170W	1/2000-12/2004
140W	1/2000-12/2004
110W	1/2000-12/2004

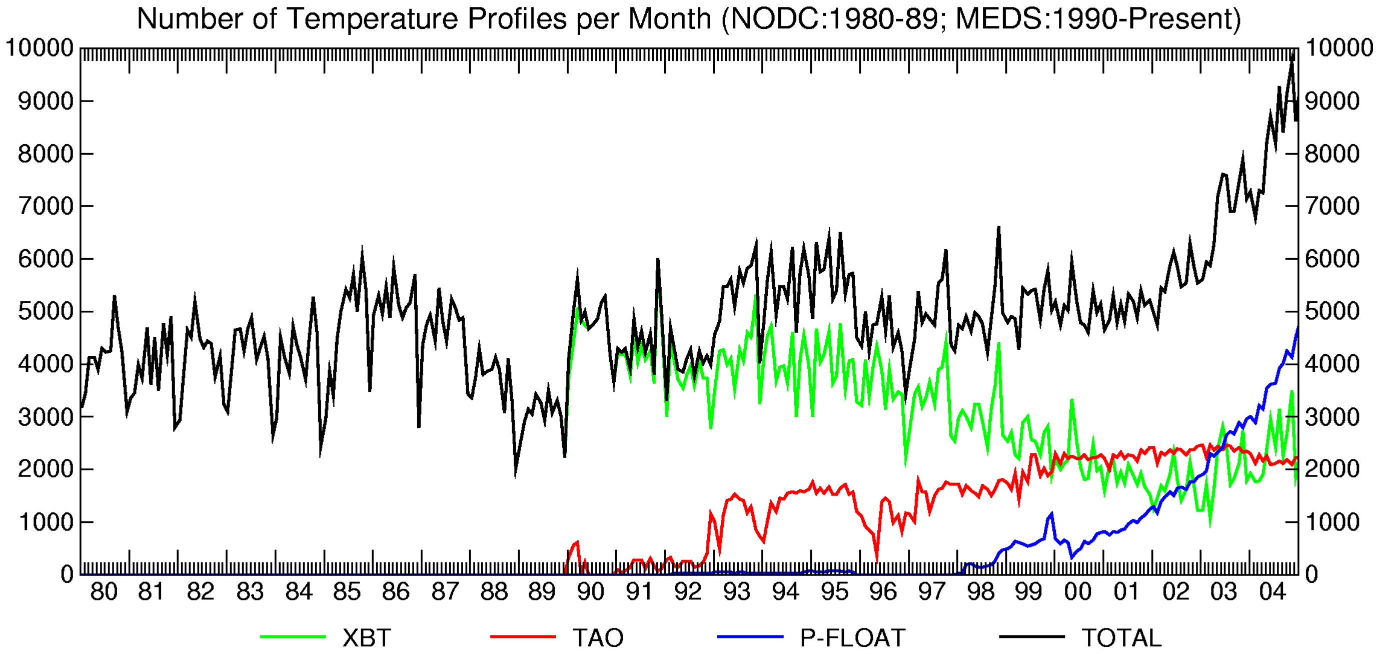


Figure 1. Monthly counts of temperature profiles used in GODAS.

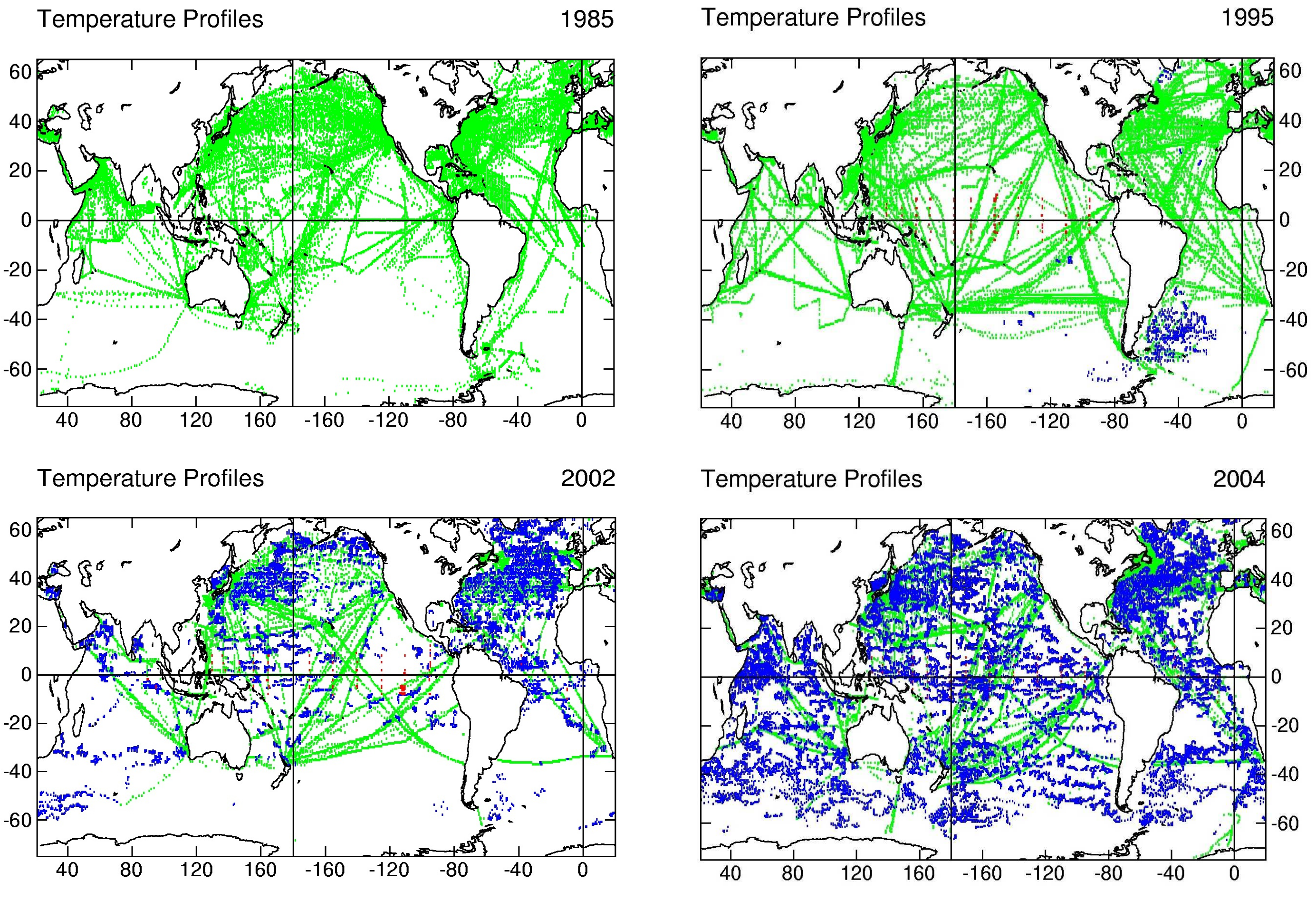


Figure 2. Annual distributions of temperature profiles. XBTs - green, Moorings - red, Argo and Argo-like floats - blue

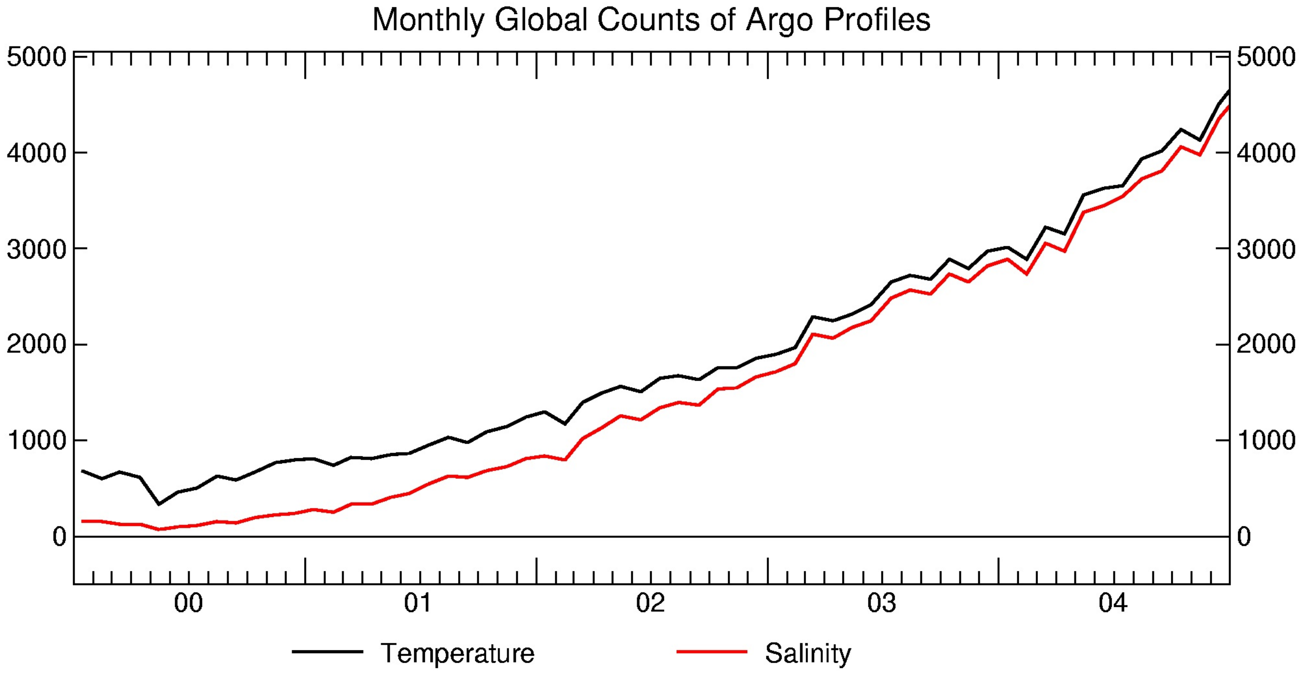


Figure 3. Monthly counts of Argo temperature and salinity profiles used in Argo.

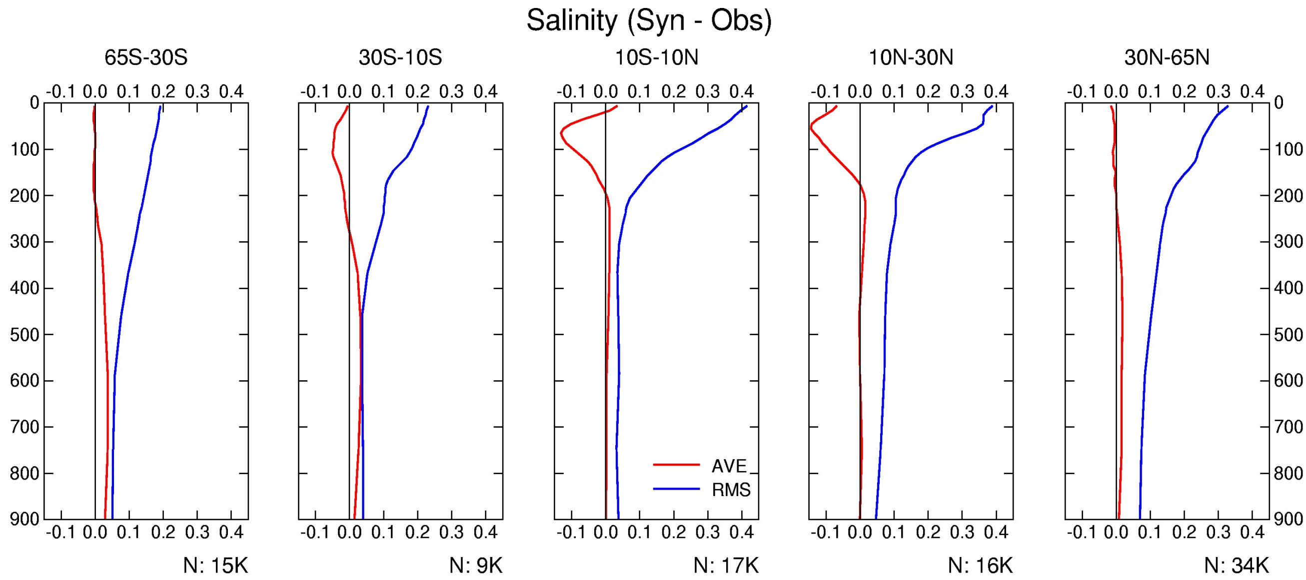


Figure 4. Comparison of synthetic salinity profiles with Argo salinity profiles.

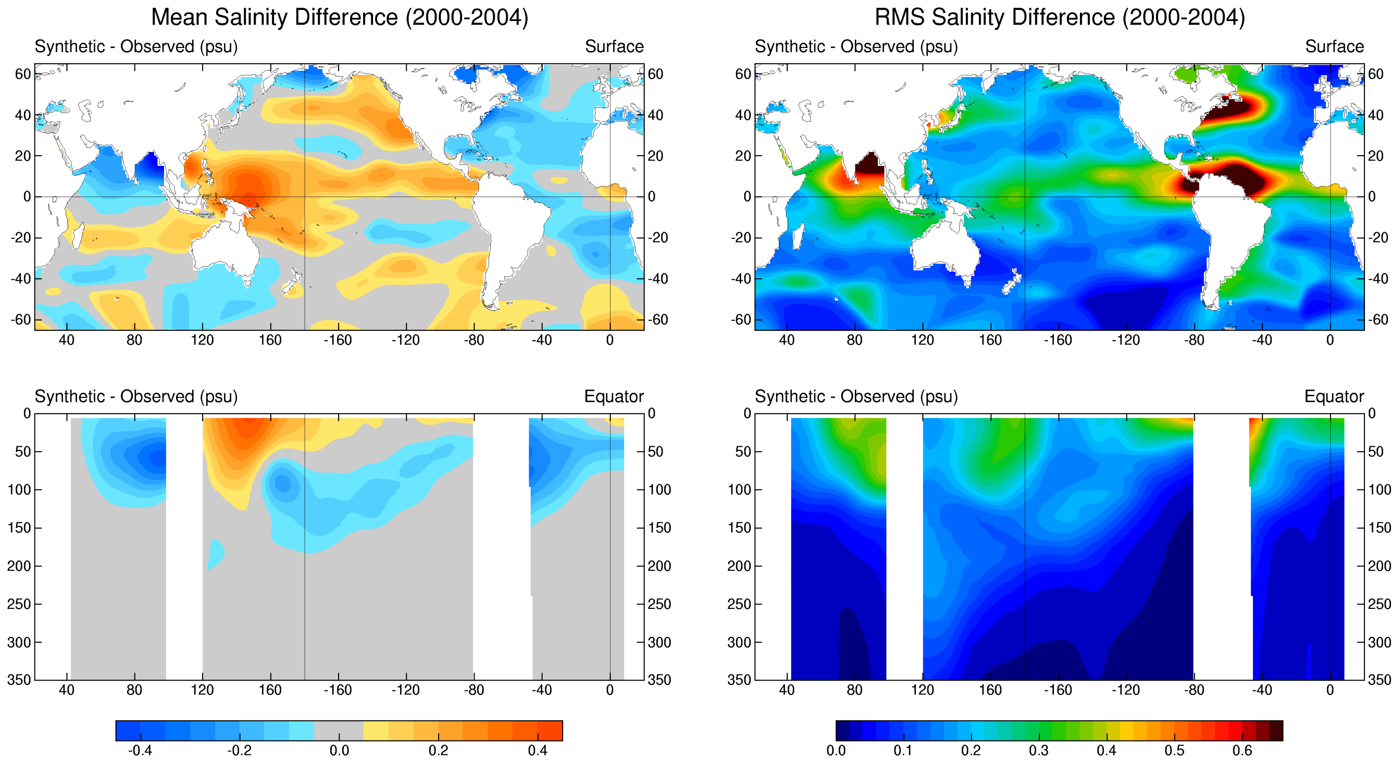


Figure 5. Comparison of synthetic salinity profiles with Argo salinity profiles. Mean difference (top) and RMS difference (bottom) mapped to the model grid.

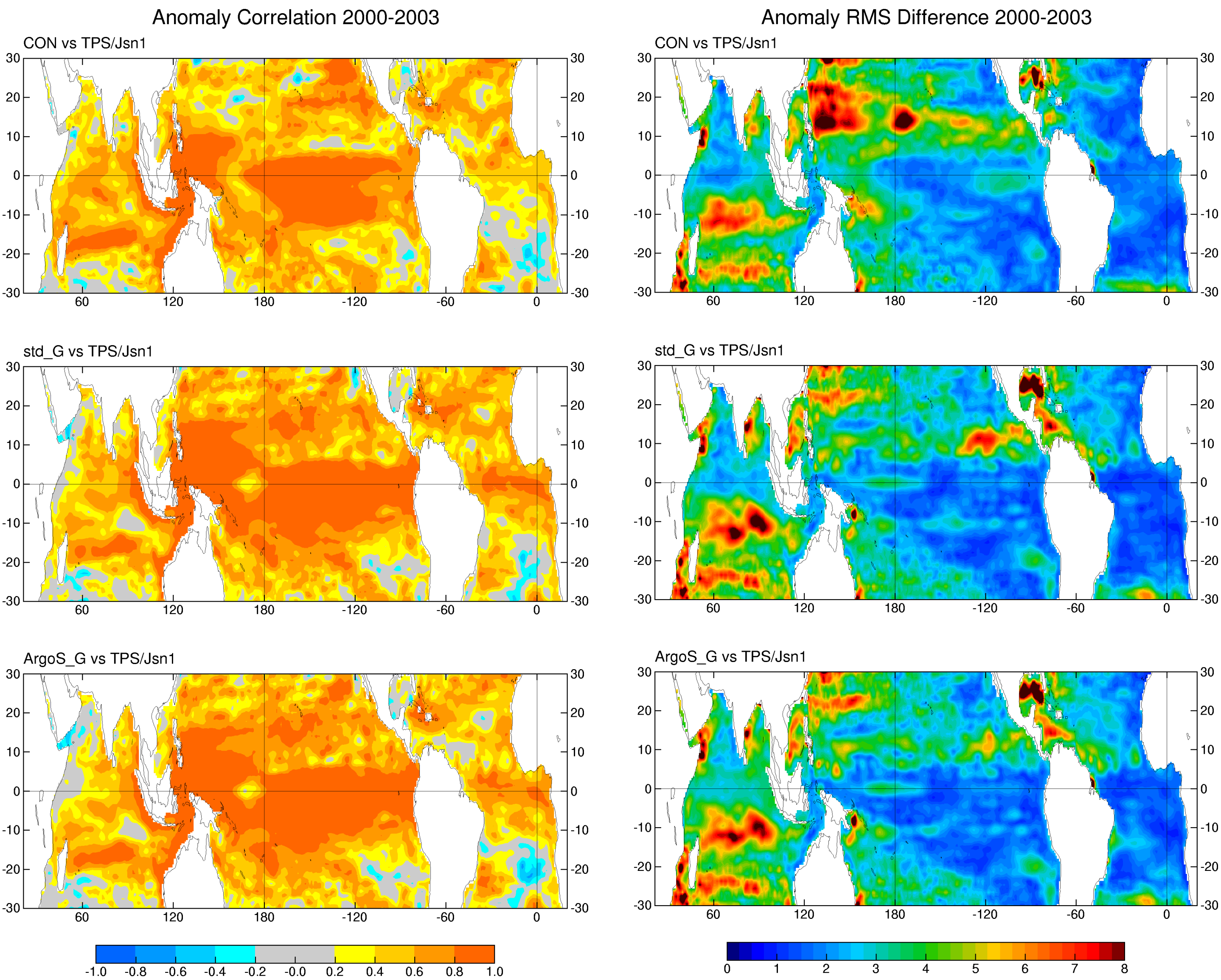


Figure 6. Correlation and RMS differences between model and TOPEX/Jason-1 SSH anomalies. Top to bottom: the control, the standard GODAS, the GODAS assimilation of Argo salinity.

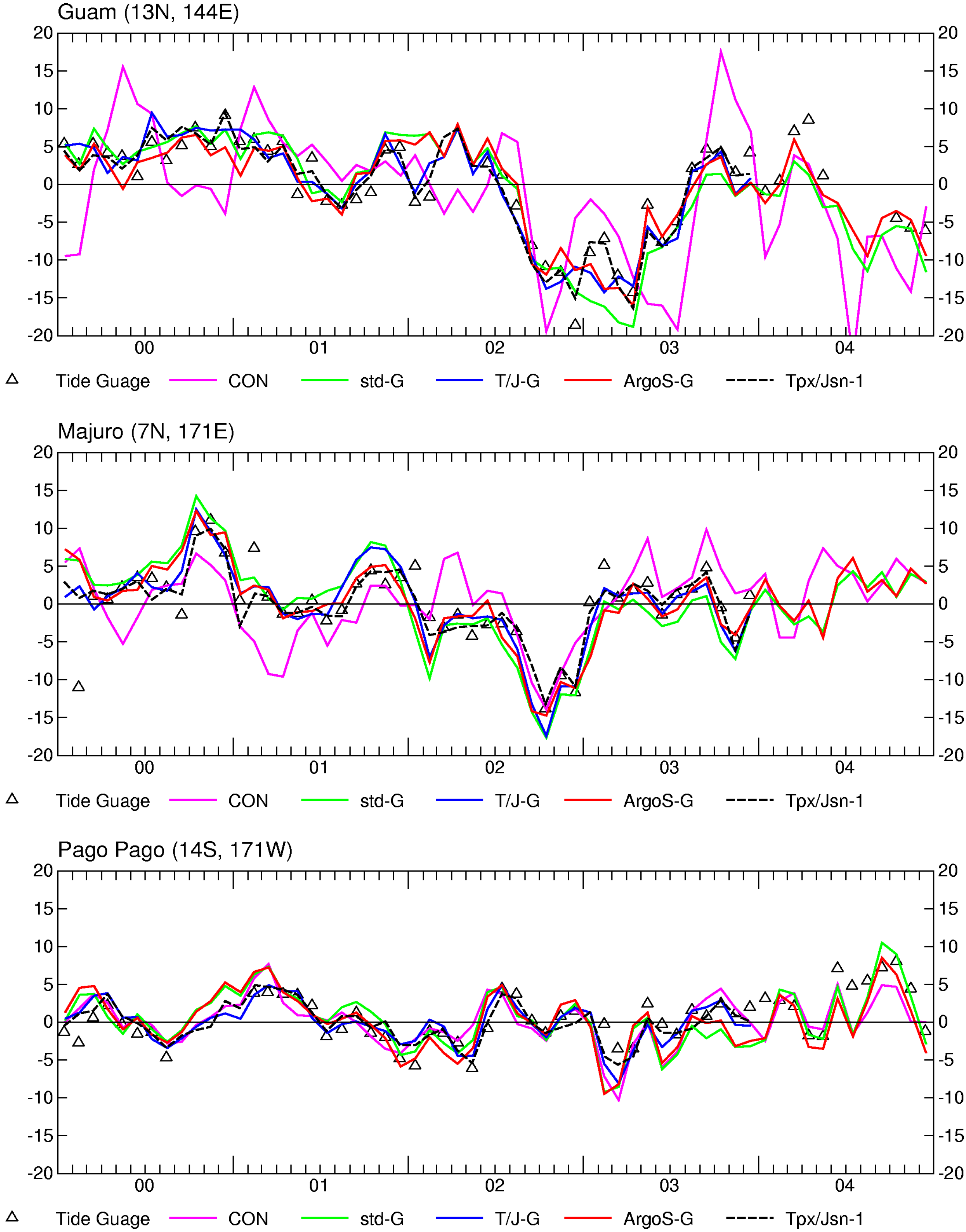
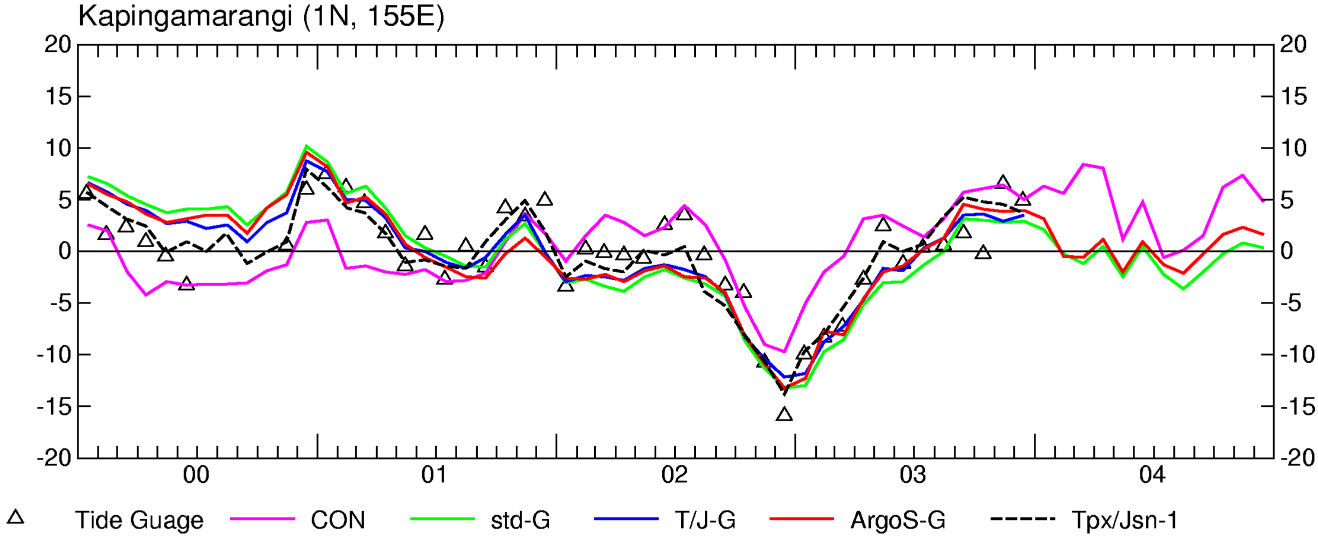
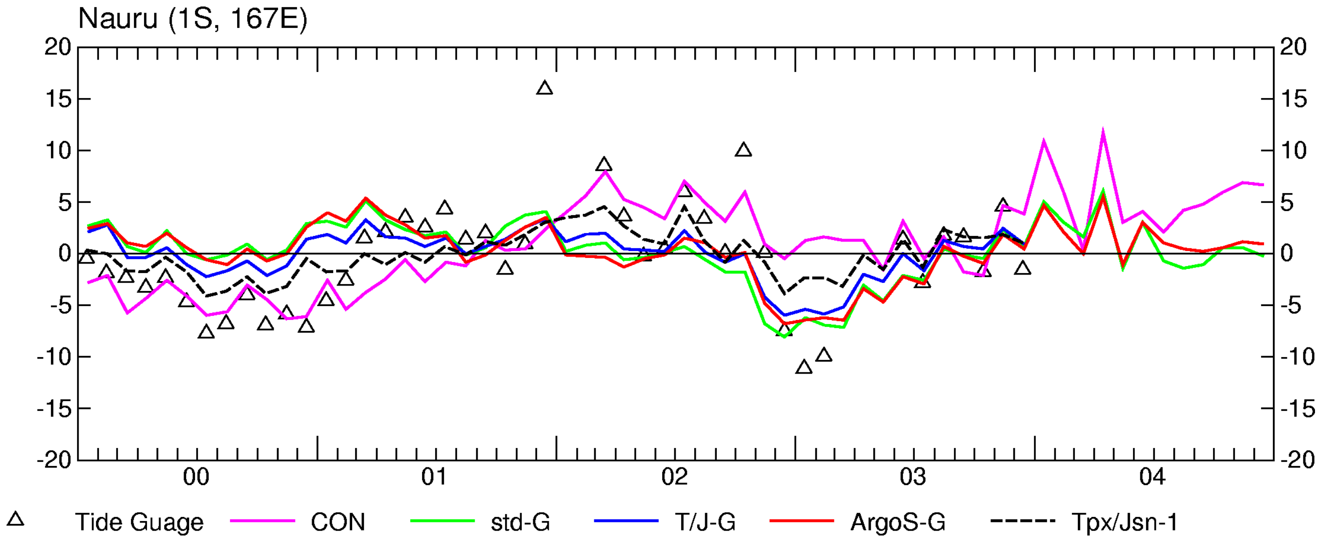


Figure 7a. Comparison of tide gauge SSH with model SSH at Guam, Majuro and Pago Pago.





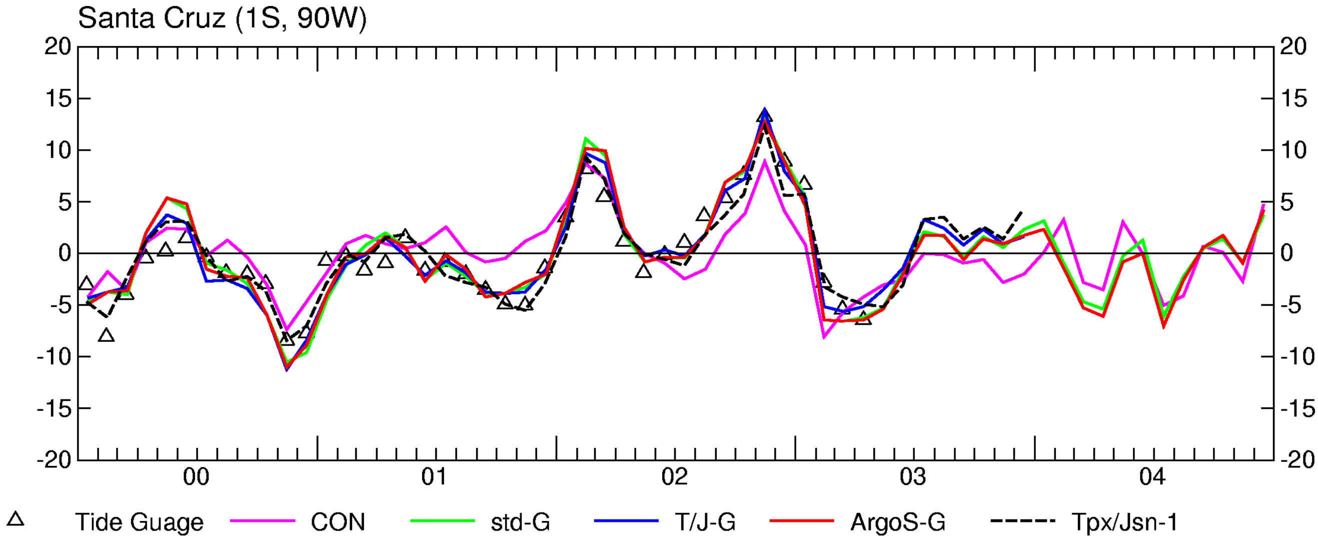


Figure 7b. Comparison of tide gauge SSH with model SSH at Kapingamarangi, Nauru and Santa Cruz.

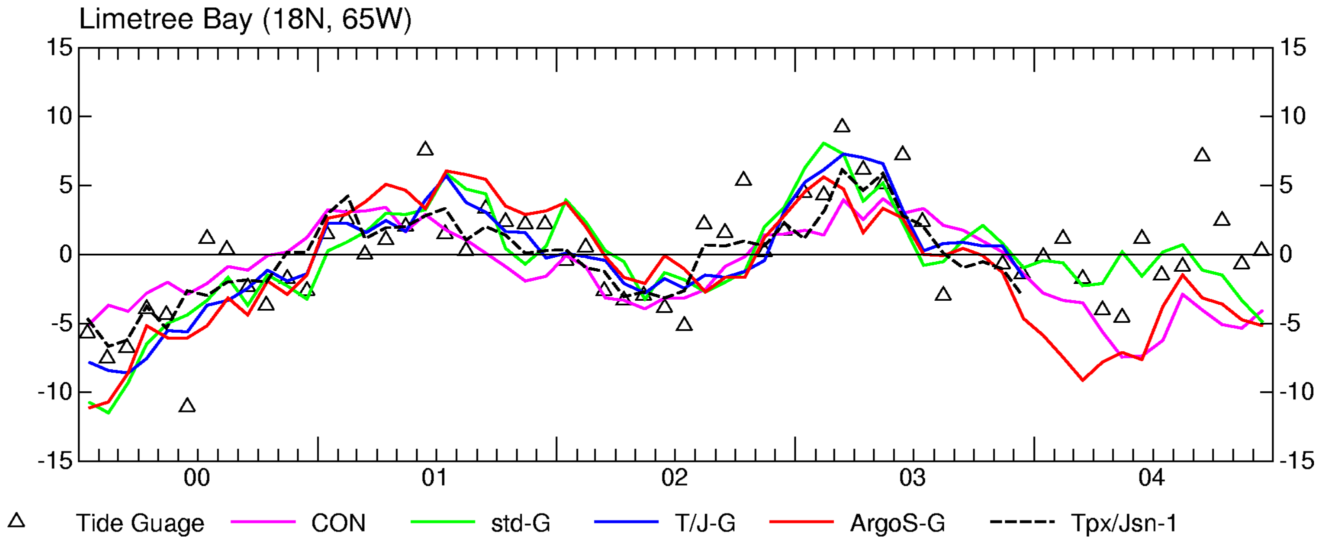


Figure 7c. Comparison of tide gauge SSH with model SSH at Limetree Bay.

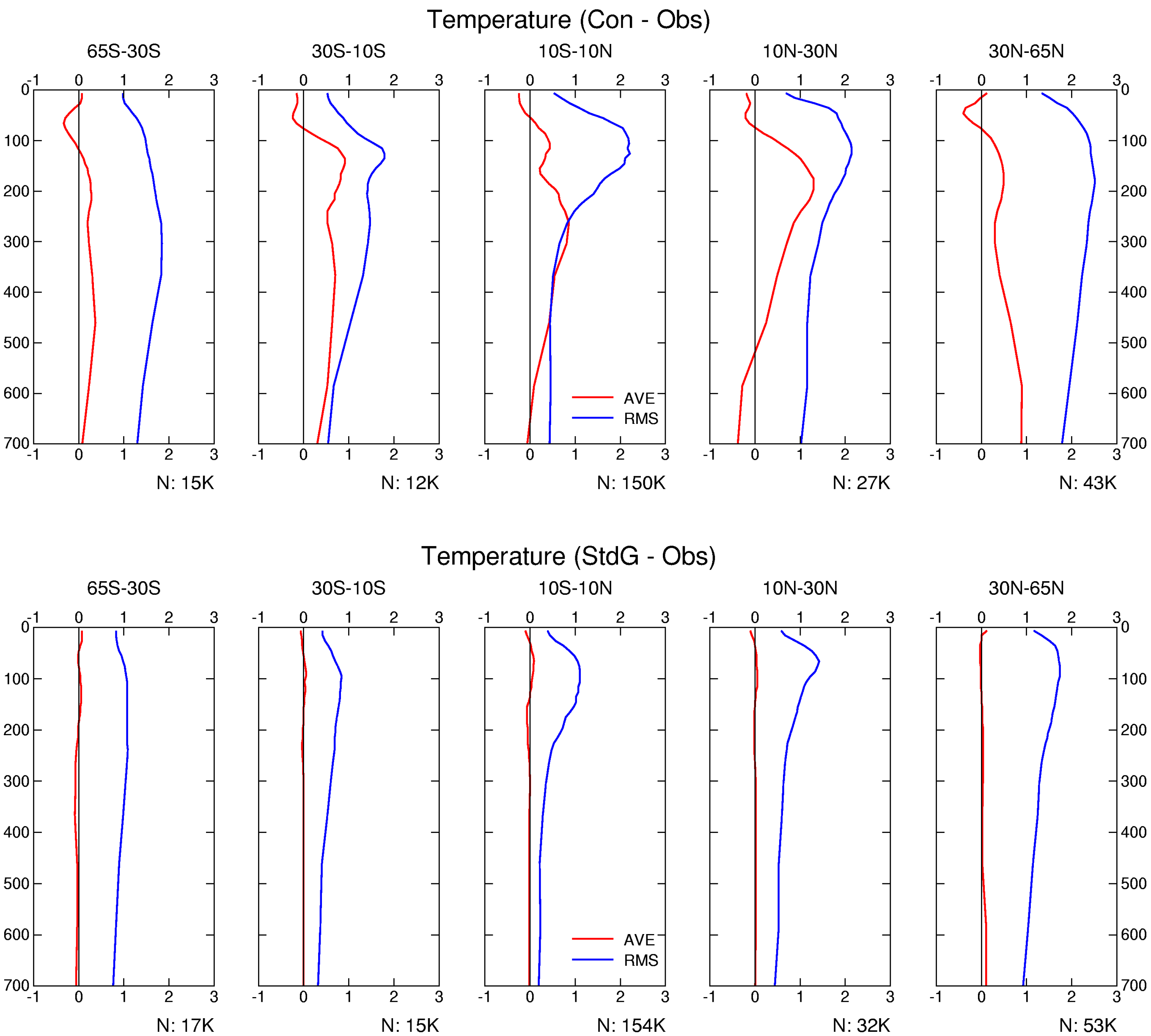


Figure 8a. Comparison of model and observed temperature profiles. Top: Control. Bottom: Std GODAS.

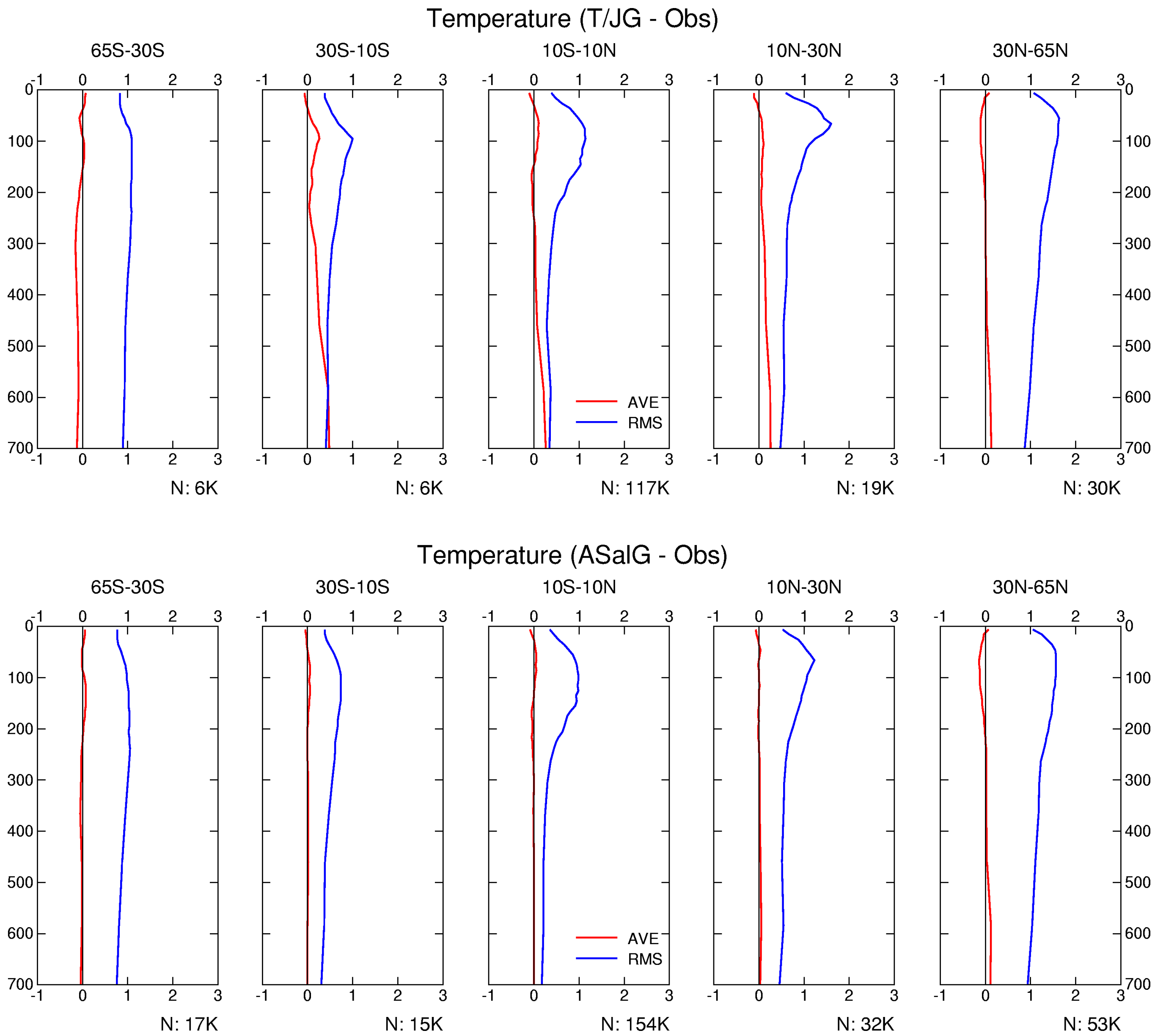


Figure 8b. Comparison of model and observed temperature profiles. Top: TPX/Jsn GODAS. Bottom: Argo Salinity GODAS.

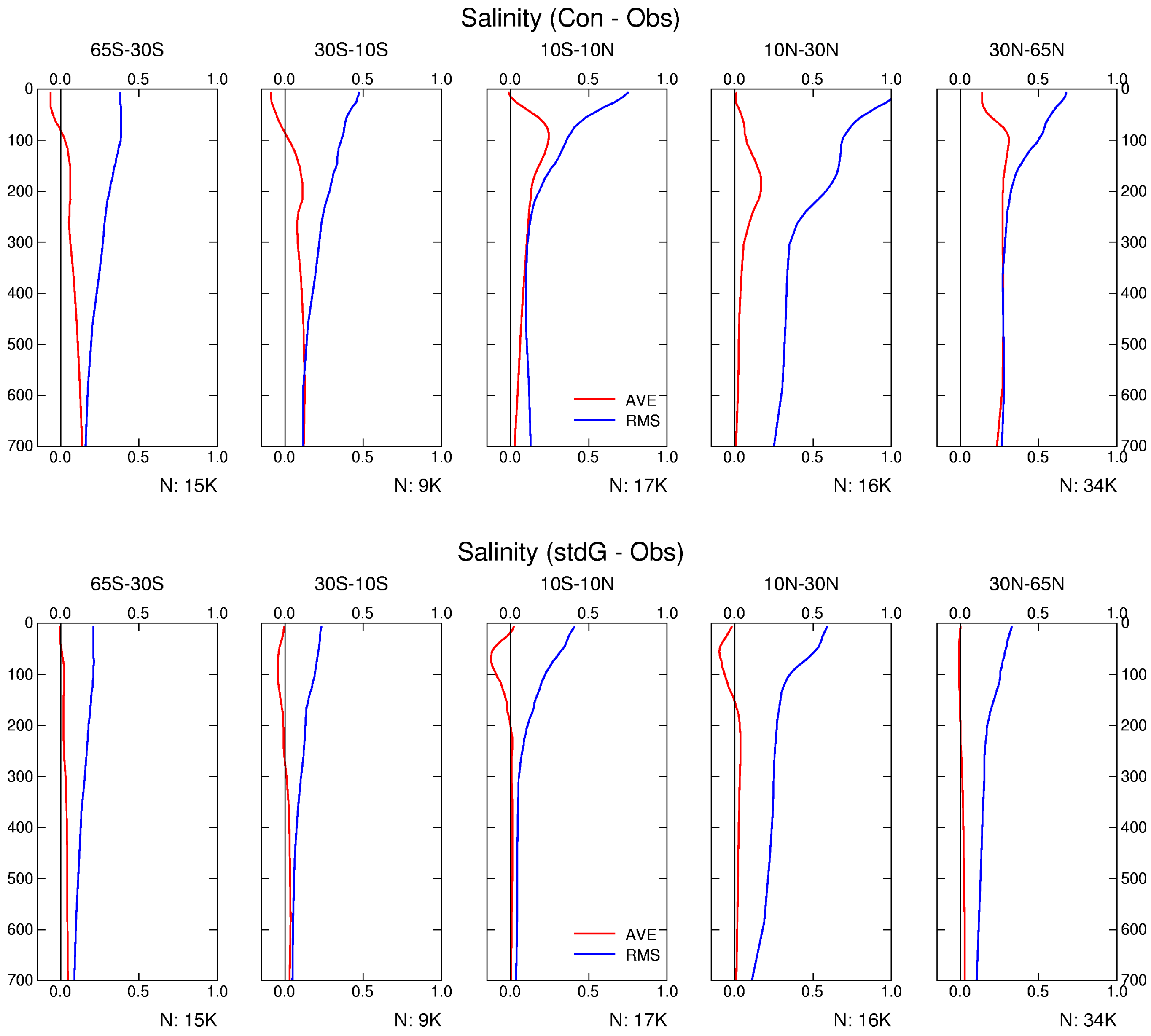


Figure 9a. Comparison of model and observed salinity profiles. Top: Control. Bottom: Std GODAS.

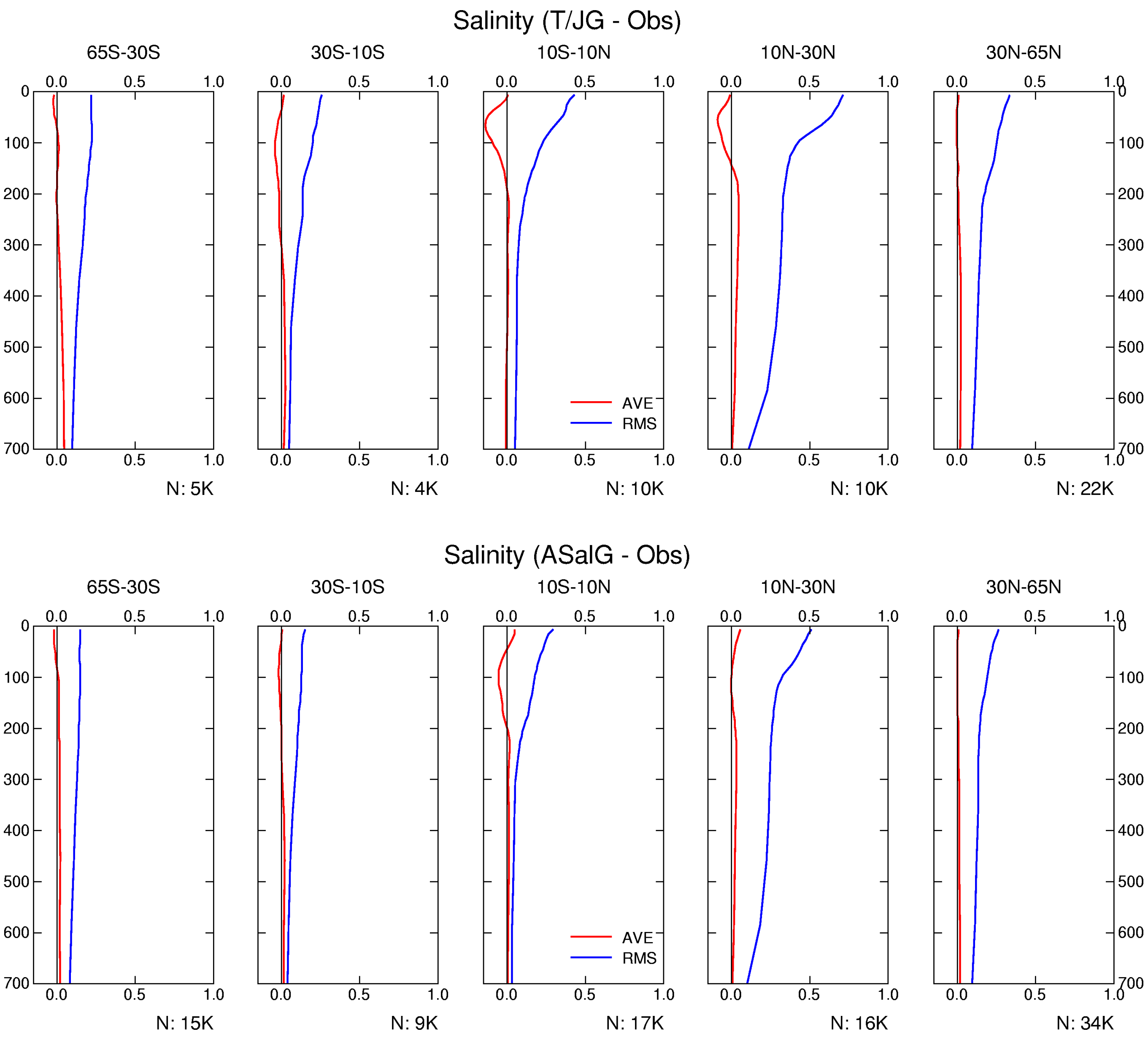


Figure 9b. Comparison of model and observed salinity profiles. Top: TPX/Jsn GODAS. Bottom: Argo Salinity GODAS.

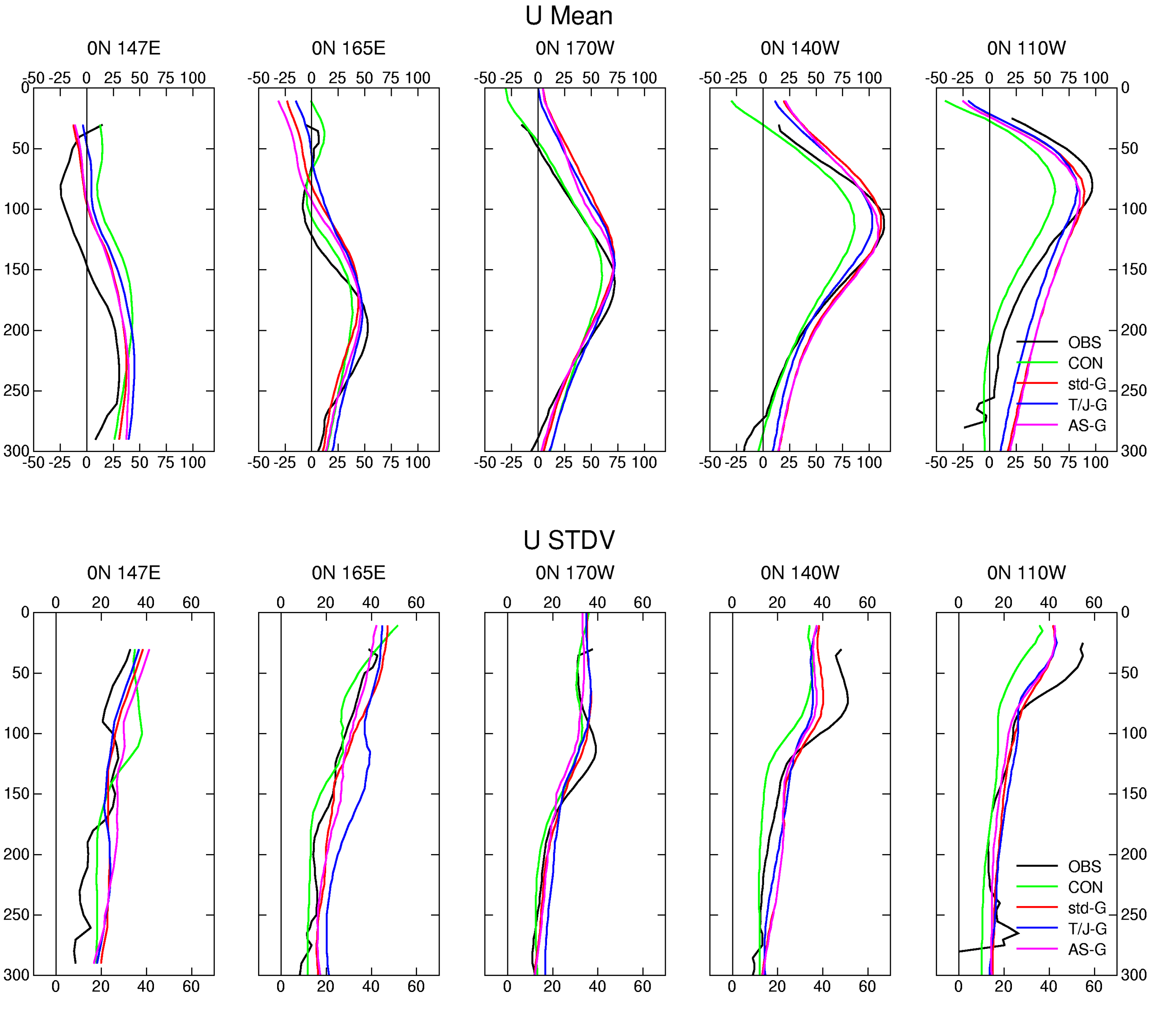


Figure 10. Comparison of model and observed equatorial zonal velocity profiles. Top: Mean. Bottom: St. Dev.